Global profile training database for satellite regression retrievals with estimates of skin temperature and emissivity[*]

Eva E. Borbas[1], Suzanne Wetzel Seemann[1], Hung-Lung Huang[1], Jun Li[1], and W. Paul Menzel[2]

[1]Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin-Madison

[2]NOAA/NESDIS Office of Research Applications, Madison, WI

1

Abstract

Regression retrievals of atmospheric properties require a global dataset of temperature, moisture, and ozone profiles in addition to estimates of skin temperature and emissivity to train the regression. A new data set consisting of approximately 12,000 global profiles of temperature, moisture, and ozone has been created, drawing from NOAA-88, ECMWF, TIGR-3, ozonesondes, and desert radiosondes. In addition, a skin temperature and emissivity value has been assigned to each profile. In earlier satellite regression retrieval algorithms, skin temperature and emissivity were assigned relatively randomly to each profile. In this paper, we present a more physical basis for characterizing the surface. New skin temperature estimates are based on a study of the skin temperature/surface air temperature difference measured by ground-based measurements, and a global ecosystem-based emissivity is developed. Application of the database to MODIS MOD07 atmospheric retrievals is presented.

Characterizing the profiles

The new training database of global profiles (called SeeBor v3) consists of 12,245 global profiles of temperature, moisture, and ozone at 101 pressure levels for clear sky conditions. The profiles are taken from NOAA-88 (Seemann et al. 2003) (44 % of total profiles), an ECMWF training set (Chevallier 2001) (34%), TIGR-3 (Chedin et al. 1985) (9%), ozonesondes from 8 NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) sites (www.cmdl.noaa.gov) (8%), and radiosondes from 2004 in the Sahara desert (5%). Quality checks were applied to all the profiles along with the following saturation criteria: for clear sky conditions, the relative humidity (RH) value of the profiles must be less than 95 % at each level below the 250 hPa pressure level. In addition to adding the new radiosondes and ozone profiles, it is required that the original top of sounding pressure be no greater than 30 hPa for temperature and moisture profiles and 10 hPa for

ozone. A technique to extend the temperature, moisture, and ozone profiles above the level of existing data that insures physically consistent behavior near the top of the troposphere was implemented. Where ozone data were not included with the original profiles, a regression-based algorithm for deriving ozone profiles was used (personal communication with Paul van Delst).

In satellite retrievals of atmospheric profiles using a synthetic regression retrieval algorithm, such as MODIS MOD07 retrievals (Seemann et al. 2003) and ATOVS retrievals (Li et al. 2000), radiance calculations for each training profile are made using a 101-pressure layer transmittance model. The calculated radiance/atmospheric profile pairs are then used to derive the regression relationship. The forward model calculations require a skin temperature and emissivity value for each profile. In the past, skin temperature and emissivity were assigned relatively randomly to each profile. Original NOAA88 emissivity spectra assigned to training profiles in MODIS had two values (0.84 from 3.7 μm to 4.8 μm and 0.95 from 9.0 μm to 13 μm) with standard deviation 0.15, 0.03 and a linear interpolation for wavelengths in between. In the same dataset, the difference between the surface air temperature and the skin temperature assigned to the training profiles was a random number with a mean of 0 and a standard deviation of 10. In the next two sections, the new approach for deriving a more physically based skin temperature and emissivity are outlined.

Emissivity

Infrared surface emissivity spectra for 16 ecosystem categories defined by the International Geosphere and Biosphere Programme (IGBP), as a function of month and latitude band were created using MODIS MOD11 emissivity data (http://www.icess.ucsb.edu/modis/modis-lst.html) and emissivity laboratory measurements. These latter ones were collected from the MODIS UCSB Emissivity Library (www.icess.ucsb.edu/modis/EMIS/html/em.html) and from the Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Spectral Library (JPL, http://speclib.jpl.nasa.gov).

Laboratory measurements of emissivity were used to choose 7 inflection point wavelengths necessary to characterize the shape of most land surface emissivity spectra. Then, the laboratory emissivity spectra of 5 common surface materials were used to derive an emissivity at these 7 wavelengths, called our "baseline" spectra. Fig. 1 shows the spectra from Nebraska, Oklahoma, Massachusetts, a sandy soil, and a dry grass that were used to derive the baseline emissivity

Monthly averaged, global MODIS land surface emissivity from the MOD11 product was used to adjust the magnitude of baseline emissivity spectra at the inflection points to determine the emissivity that was assigned to the training profiles. The emissivity at MOD11 wavelengths (3.7, 3.9, 4.0, 8.5, 11.0 and 12.0 μm) was averaged by IGBP ecosystem, month, and latitude band. Next, a procedure involving the inflection points and the baseline emissivity was used to derive a spectrum for a given ecosystem, month, and latitude. This approach was performed for all Terra and Aqua MOD11 data for 4 years (Terra) and 2-1/2 years (Aqua). A lookup table was generated

in order to apply the emissivity to any profile given the month, latitude, and IGBP ecosystem. Figure 2 contains a comparison among the spectra of all ecosystems for one latitude band and one month over 4 years.
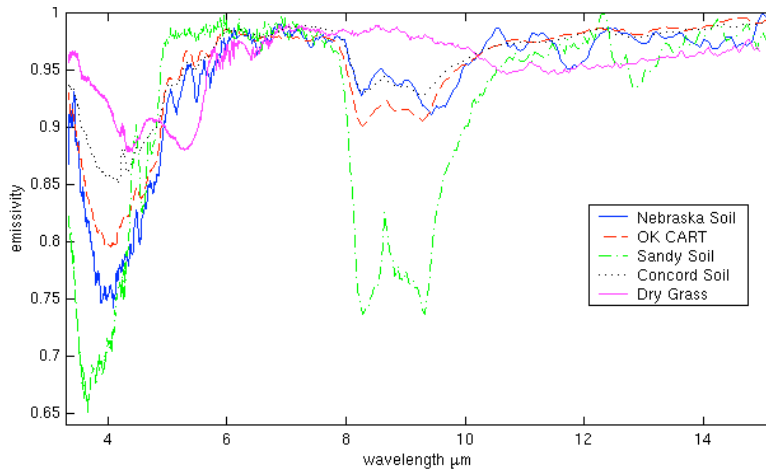

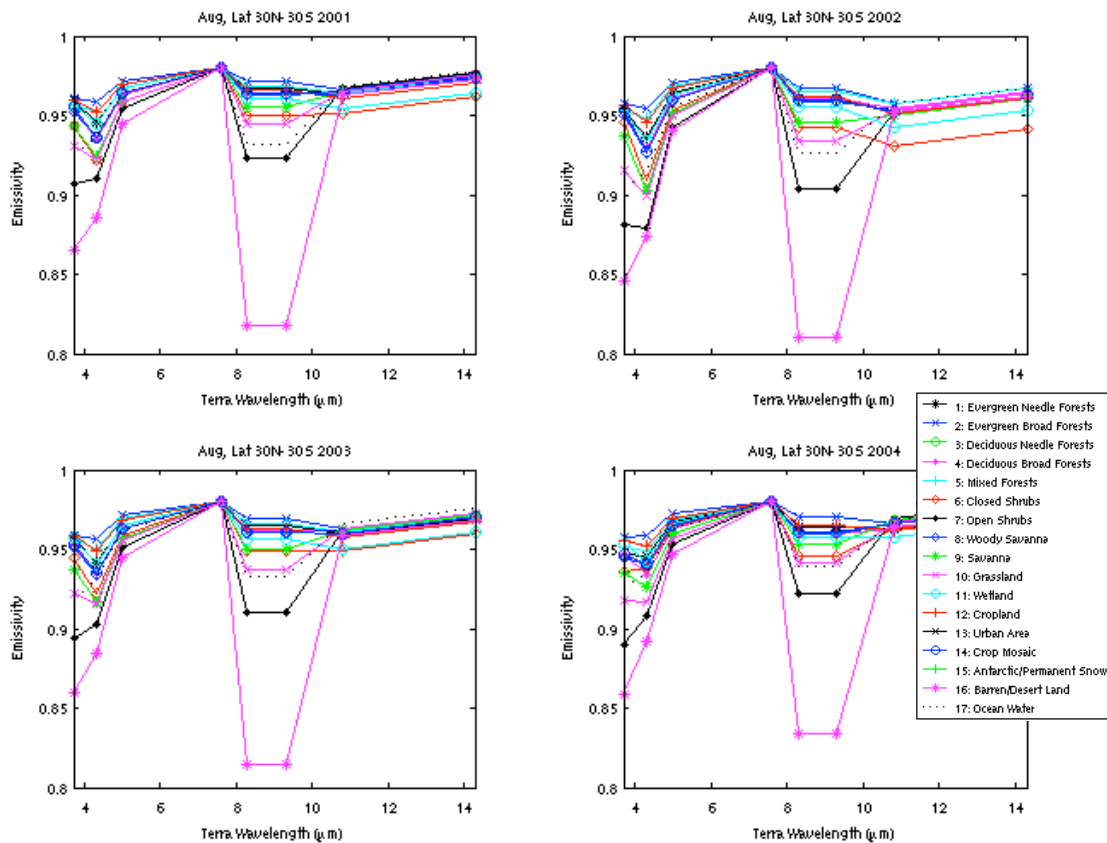Fig. 1: Laboratory-measured emissivity spectra of 5 soils and grasses used to define our "baseline emissivity"

Fig. 2: Emissivity for 17 IGBP ecosystem classes derived from the laboratory "baseline" emissivity and measured MODIS MOD11 emissivity. Emissivities shown are for the latitudes between 30N-30S, for four years in the month of August: 2001 (top left), 2002 (top right), 2003 (bottom left), and 2004 (bottom right).

The ice/snow and seawater emissivity is assigned to the profiles using a different method. Ice and snow emissivity is based on the average of a number of ice and snow laboratory measurements (Fig 3a). The seawater emissivity is determined by the Smith/Wu emissivity model (Wu and Smith 1997), which is a function of wind speed, viewing zenith angle and channels (see Fig 3b). In the training dataset the viewing angle was set to 0 degrees and the wind speed was assigned randomly to the profiles where actual wind speed data were not available. To generate the random wind speed, the mean (6.6 m/s) and twice standard deviation (3.3 m/s) of 1900 clear scene ECMWF profiles were used.
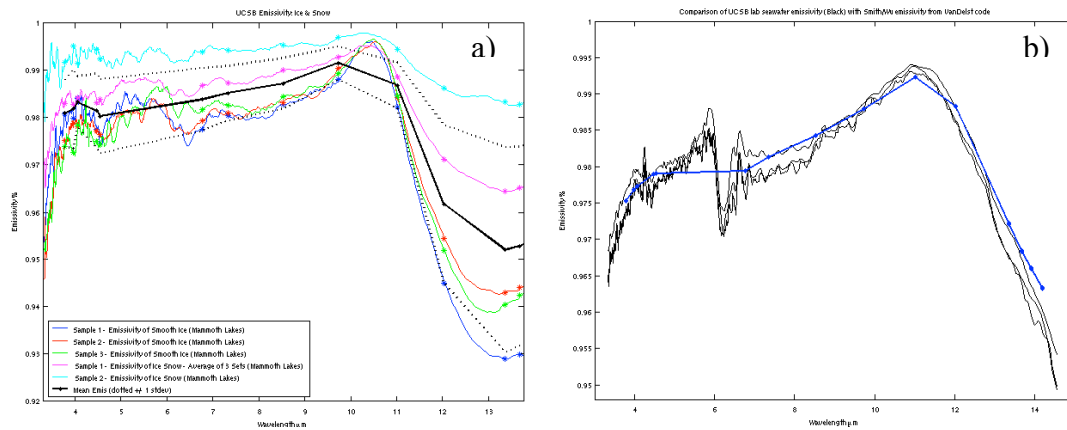

Fig. 3 a): Ice and snow emissivity (black solid line) is based on the average of a number of ice and snow laboratory measurements from the MODIS USCB emissivity library. b) Seawater emissivity (blue solid line) is based on the Smith/Wu emissivity model.

Skin temperature

Global skin temperature over land is characterized as a function of surface air temperature, solar zenith angle (3 categories), and azimuth angles (8 categories). To build the relationship, skin temperature measurements from the Atmospheric Radiation Measurement (ARM) Program's, Southern Great Plains (SGP) site in Oklahoma were used together with radiosonde data from the period April 2001 to October 2003. The difference between the IR thermometer measured surface skin temperature and the radiosonde surface air temperature for 124 clear sky cases is shown as a function of solar zenith and azimuth angles in Figure 4. The relationship defined by Fig. 4 was used to assign a skin temperature to all profiles.
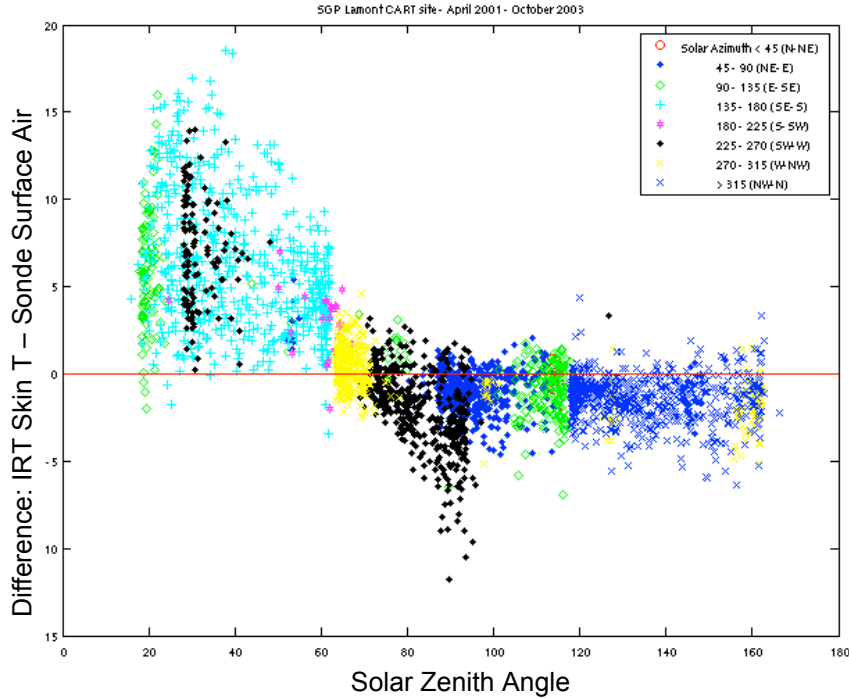
Fig 4: Skin Temperature and Surface Air Temperature relationship for the SGP CART site based on clear sky observations between April 2001 and October 2003. Points are colored according to solar azimuth category.

An application to MODIS retrievals

The training dataset with new emissivity and skin temperature is routinely tested on MODIS atmospheric retrieval products (called MOD07). Comparisons of MODIS-derived Total Precipitable Water (TPW) are made with NWP-, GOES-derived, and ground based measurements of TPW over three ARM sites: SGP-Oklahoma, Tropical Western Pacific, and Alaska for 124 cases that were determined to be clear sky by manual inspection of satellite imagery.

A comparison between TPW derived from the MODIS MOD07 algorithm using the old (NOAA88) training dataset with randomly applied skin temperature and emissivity and that using the new training dataset with its physically assigned skin temperature and emissivity can be seen in Figure 5. In each panel, radiosonde-, GOES- and MOD07-derived TPW values are plotted against the ground-based Microwave Water Radiometer (MWR) -derived values. Panel a) shows the results when the NOAA88 training data was used in the MOD07 calculation. In this case, the Pressure–layer Fast Algorithm for Atmospheric Transmittances (PFAAST) model (Hannon et al. 1996) was used for the forward calculation. For these 124 clear sky cases from April 2001 to September 2003 over the SGP site, we found a 1.61 mm bias and a 3.99 mm rms difference between the MWR TPW and MOD07 TPW products. Panel b) shows the results for MODIS retrievals with the same forward model but with the new training dataset. For all (wet and dry together) cases the bias is reduced to 1.02 mm and the rms difference improves to 2.68 mm. In

panel c), the MODIS retrievals used the same training data as in panel b), but with a different forward model used in the MOD07 regression coefficient calculation: the prototype Community Radiative Transfer Model (pCRTM, formerly OPTRAN) (van Delst, http://www.ssec.wisc.edu/~paulv/Fortran90/CRTM/Prototype/). Using pCRTM, the bias was improved to 0.3 mm and the rms difference to 2.5 mm.
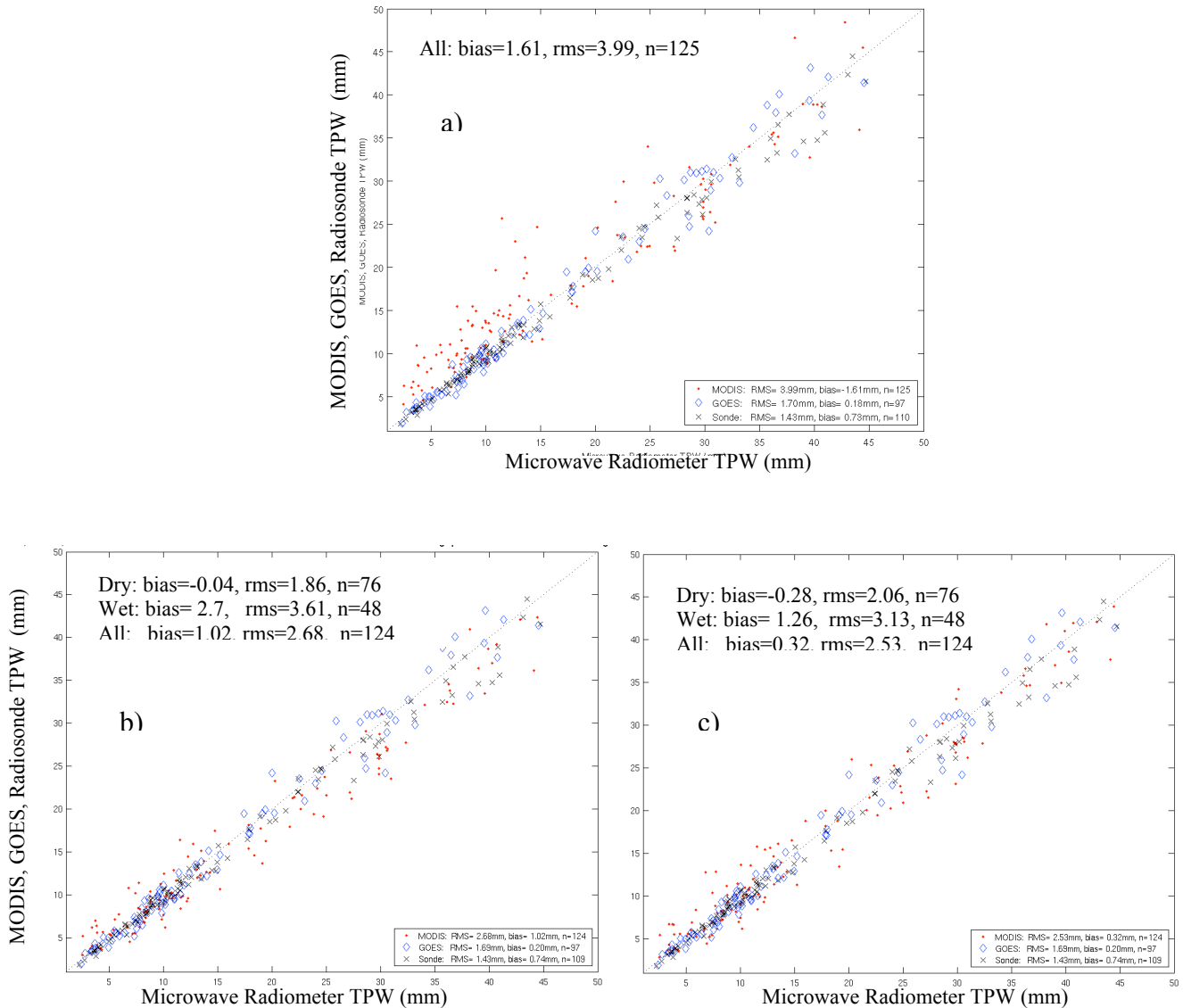

Fig. 5: Terra MODIS (red dots), GOES-8 and -12 (blue diamonds), and radiosonde (black crosses) TPW is compared to that measured by the ground-based ARM SGP microwave water radiometer for 124 clear sky cases from April 2001 to September 2003. Results from three different training data sets are shown here: a) illustrates the result when the old NOAA88 training data was used in the MOD07 retrievals, b) and c) show the results with the new training dataset when PFAAST (b) and the pCRTM model (c) was used in the forward calculation. The b) and c) cases are also divided into dry and wet atmospheres, where dry is defined as TPW <= 17mm.

MOD07 Terra and Aqua near-real time products (including temperature, lifted index, ozone, and mixing ratio) computed from direct broadcast data are used to generate comparisons with the GOES data at the Space Science and Engineering Center (SSEC), Madison, Wisconsin. An example of a GOES-derived TPW comparison is shown in Figure 6. Time series of MWR-, GOES-, radiosonde-, and MOD07 derived TPW values at the SGP site and over SSEC are also plotted daily. See these images and comparisons at *http://cimss.ssec.wisc.edu/modis/mod07*.
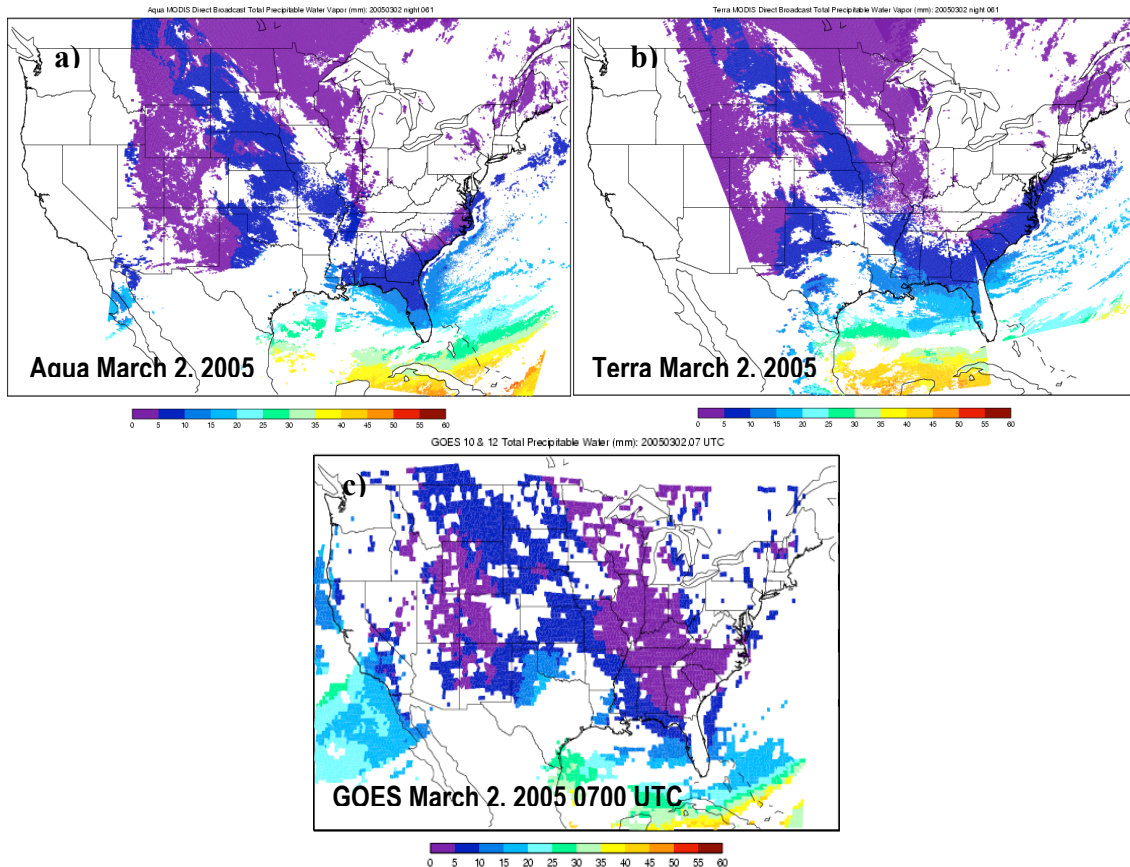

Fig. 6: TPW comparison for March 2, 2005 in the morning. a) and b) show the MODIS derived TPW field from the Aqua and Terra satellite, respectively, c) is the GOES TPW field at 0700 UTC.

Conclusions

Historically, synthetic regression retrievals have relied on training data sets that made little attempt to physically characterize the surface. In this paper, a new global training data set that combines profiles from a number of sources is presented. Associated with each profile in the data set is a physically based characterization of the surface skin temperature and surface emissivity. Application of this SeeBor v.3 training data on MODIS MOD07 retrievals of total precipitable water show good improvement over the NOAA-88 training data set. With the new training data

and an updated forward model, the rms difference between MOD07 TPW and the ARM SGP MWR was reduced from 4 mm to 2.5 mm.

Future plans

We are planning to add more global radiosonde profiles to the dataset with improved handling of the upper atmosphere above the levels of existing radiosonde data. In the near future the ecosystem-based emissivity will be replaced by a non-ecosystem-based, global gridded emissivity derived from 3 years of MODIS MOD11 emissivity products and high spectral resolution laboratory measurements of emissivity. The skin temperature parameterization will be expanded to include other areas of the globe.

Acknowledgements

References

Chedin, A., Scott, N.A., Wahiche, C. and Moulinier, P., 1985. The improved initialization inversion method: a high resolution physical method for temperature retrievals from satellites of the Tiros-N series, *J. Clim. Appl. Meteor.*, 24, pp 128-143.

Chevallier, F., 2001. Sampled databases of 60-level atmospheric profiles from the ECMWF analyses. EUMETSAT/ECMWF SAF programme, *Research Report* No. 4.

Hannon, S., L. L. Strow, and W. W. McMillan, 1996. Atmospheric infrared fast transmittance models, A comparison of two approaches, in *Proceedings of SPIE*, *2830*, 94-105.

Li, J., W. Wolf, W. P. Menzel, W. Zhang, H-L. Huang, and T. H. Achtor, 2000. Global Sounding of the Atmosphere from ATOVS Measurements: The Algorithm and Validation, *J. Appl. Meteor.*, 39, 1248-1268.

Seemann, S. W., Li, J., W. Paul Menzel, and L. E. Gumley, 2003. Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances, *J. Appl. Meteor.*, Vol. 42, pp. 1072-1091.

Wu, X., and Smith W.L., 1997. Emissivity of rough sea surface for 8-13μm: modeling and verification. *Appl. Opt.*, 36, 2609-2619.